Chapter 1

Introduction

1.1 Overview of study

My work has dealt with a sequence of basic plasma physics questions with the aim to better understand the nature of high speed flow of a magnetized plasma. One important aspect of this work is the physics of turbulent flow states. The device that makes this investigation feasible is the CTIX plasma accelerator. However, our great success at designing and operating this accelerator has been founded on only a very rudimentary model of the plasma physics involved. Like early hominids, not understanding combustion chemistry hasn't stopped us from rubbing two sticks together and making fire.

And so, as I have endeavored to do something new and useful with CTIX, I have been repeatedly confronted with fundamental questions of regarding the plasma physics that makes it all work in the first place. I have tried to answer these questions as they have become experimentally accessible, and I have attempted to synthesize our results into improved models of what is actually going on inside the plasma. The individual results I have produced are interesting in themselves, in that they advance our understanding of the inner workings of CTIX-like plasma accelerators; but as a collection they have a more general usefulness by providing accurate knowledge of initial con-

ditions and plasma parameters for use when analyzing the experimental data that address universal phenomena such as magnetohydrodynamic (MHD) turbulence.

I have organized my results in an sequence from Chapter 2 to Chapter 7 that logically build on one another toward establishing the key prerequisites for an MHD turbulence experiment. Chapter 2 examines the structure and dynamics of the compact toroid's magnetic field. This information is critical for properly analyzing the Reconnection/Compression experiments described in Chapter 3, and the outcome is a measurement of the so called anomalous resistivity (or magnetic diffusivity) of the plasma as described in Chapter 4. Together this work provides the initial conditions for the drift section measurement of kink dynamics and the wire target turbulence experiments discussed in Chapter 9 and 10.

Chapter 5 describes measurement of the electron temperature of the plasma and looks at the dynamics of energy conversion during the process of interaction with a transverse magnetic field. The knowledge about the electron temperature helps to construct an accurate model of the ionization of helium under our range of conditions. Helium enters the equation because of its ability to emit light brightly when bombarded with plasma electrons. This optical emission provides several diagnostic opportunities. The first is explored in Chapter 6; using a high resolution spectrometer we were able to measure the Doppler shift of spectral line of He II ions, in doing so we measured the velocity of the plasma in previously inaccessible locations in the vessel. Several of these preliminary results are combined in Chapter 7 where I calculate values of the Reynolds numbers that occur in the CTIX plasma flow. The dimensionless Reynolds numbers play a vital role in determining the properties of a fluid flow, and the issues regarding turbulence that we can address with CTIX are focused on how experimental observable change with changing Reynolds number.

From Chapter 8 on we direct our attention to the experiments in the drift section of CTIX where conditions are suitable for exploring MHD turbulence. Chapter 8 discusses our primary tool for investigating turbulence, a technique called Gas Puff Imaging (GPI) in which a cloud of neutral helium can be used to image plasma density fluctuations. Chapter 9 presents analysis of images

taken with fast cameras and gas puffs that show the MHD kink instability at work on the central column of plasma that carries the accelerator current after the compact toroid has entered the drift section. Chapter 10 introduces a wire target that was used in a set of experiments to act as a magnetic perturbation to the plasma flow, and presents the analysis of images that show coherent and incoherent density waves that are created in the presence of the wire target perturbation. Lastly we will compare these results with relevant ideas in turbulence theory.

Proposed future work and and a variety of technical details are included as appendices.

1.2 Structure of CTIX device

The Compact Toroid Injection eXperiment, (CTIX), is a coaxial railgun that forms and accelerates magnetized plasma rings called compact toroids (CT's). CTIX consists of a pair of cylindrical coaxial electrodes with the region between them kept at high vacuum. The outer conductor vessel is 2.5 m in length and 15.24 cm in diameter. The electrodes are connected to high voltage 50 μF capacitors and metglass passive timing delay inductors that together form the rail gun circuit. The electrically conductive CT plasma forms a sliding short between the inner and outer electrodes, and completes the path for current to flow down the center conductor, across the plasma, and back along the outer conductor. The railgun effect that accelerates the CT can be accounted for by the Lorentz $\mathbf{j} \times \mathbf{B}$ force density, where $\mathbf{j}$ is the current density driven by the external circuit, and $\mathbf{B}$ is the magnetic field created by the current flowing in circuit, (primarily down the center conductor). There are separate capacitor banks for the formation and accelerator sections that can be charged to different voltages. The final velocity of the CT can range from $V_{CT} = 5cm/\mu s$ up to $V_{CT} = 25cm/\mu s$. V_{CT} can be adjusted within this range by changing the applied accelerator voltage. The mass of the injected hydrogen CT is typically in the range of a few micrograms.

The center electrode has a larger diameter in the formation region, has a step down in diameter, and then a tapered section, and finally it has a long, slightly thiner straight section where

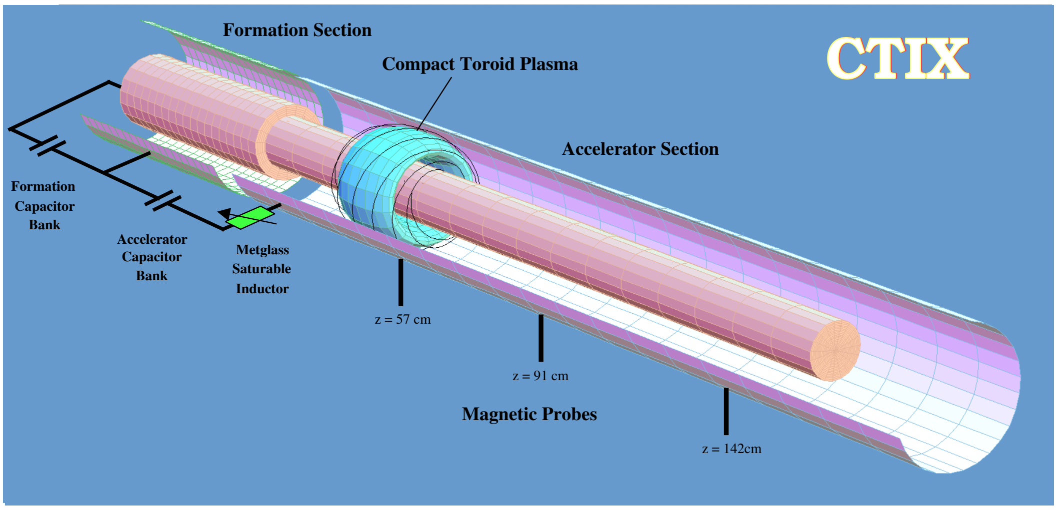

Figure 1.1: 3D view of CTIX showing magnetic probe positions and circuit schematic

most of the CT acceleration occurs. The outer electrode has a corresponding tapered section at the junction between the formation and acceleration regions. Originally the center electrode was electroplated with gold to minimize surface effects from the raw stainless being exposed to the plasma. However, after years of operation, the sustaining direct impact of massive high current discharges at gigawatt power levels has resulting in most of the gold plate in the middle of formation section becoming completely removed via ablative processes and deposited elsewhere in the vessel. Some regions near the step down edge on the center conductor (z = 20 cm) have accumulated the gold deposits as a highly textured surface that looks like cracked stucco or peeling paint. We don't know exactly what effect this surface has on the formation process, but all evidence suggests that either it does not matter at all, or it actually the improves the formation of high density compact toroids.

The possibility that this surface texture could be beneficial is interesting, and not inconceivable. Electric fields will be significantly stronger at the tips of the gold flakes than elsewhere in the bulk volume. Positive contributions to the formation process might be accounted for by some kind of hollow-cathode effect, in which the small flat spaces between the flaking gold layer and the

vessel wall act to create very efficient fast ionization of the plasma over a large surface area. Additionally, such an unusual formation boundary condition might partially account for the fact that the neutral gas break-down event is held off for such a long time (several ms) while the seed magnetic field decays until it is at just the right magnitude and field geometry, and then break-down spontaneously occurs. It is also possible that such a rough surface on the boundary of the newly forming plasma could modify the fluid velocity field, such as by exciting high k turbulence for example, which ultimately results in the mysteriously efficient fast dynamo effect that is responsible for the creation of the large internal magnetic field of every single compact toroid we generate on CTIX. The observations of extended hold-off of break-down, and unusually high flux amplification factor (~ 200), that occur during the plasma formation are two of the most basic features on the CTIX device. They are definitely in need of further explanation, and the effects of a non-trivial boundary condition should be an important element to consider in future work on the subject.

CTIX was situated so that it can inject its CT's into the Davis Diverted Torus (DDT), which is a small toroidal device that was built in order to investigate basic tokamak physics. Composed of a stainless steel toroidal vacuum vessel, major radius of 44 cm, minor radius 14 cm, which is surrounded by 7 toroidal field coils, as well as a variety of poloidal field coils, an Ohmic core, and a set of pre-ionization coils. DDT originally operated in a pulsed mode where a tokamak-like plasma was heated and confined.

However, as the focus of experiments shifted toward CTIX we ceased the full-power pulsed mode and only operated DDT with smaller currents in a continuous mode. In this mode a tokamak-like plasma is not possible or desired. Instead, we injected the CT into the vacuum field of DDT so that we can observe the interaction of the CT and the continuous toroidal field. The presence of tokamak plasma would make the diagnostic situation more difficult in certain ways, mostly because once reconnection has occurred there is no easy way to distinguish between the tokamak plasma and the CT. Without the tokamak plasma getting in the way of our diagnostics, we can look at zeroth order stopping effects, as well as post-reconnection dispersion and thermalization since the

only plasma in the device is that which originated in the CT.

The toroidal field coils of DDT have a radius of 40 cm and produce about 3 Gauss per Amp at the center of the minor axis of the vacuum vessel. They are water cooled and can produce a maximum field of 600 Gauss in continuous mode. [ref NF high beta paper]

1.3 Concept of a compact toroid plasma

A compact toroid is a magnetized plasma ring formed within a conducting vessel of coaxial geometry. The term "compact" is used because traditionally these plasmas tend to be formed between coaxial electrodes having only a modest outer radius of about 10 cm. It has a strong interior magnetic field that has a special geometry with closed flux surfaces that results in plasma particles being trapped on the field lines for much longer than the escape time due to the particle's thermal velocity.

Also, this magnetic field is self-generated by the currents flowing within the plasma ring. In this way the compact toroid is self-confined in a stable geometry that persists until the internal currents resistively die down or particles escape as certain non-trivial phenomena eventually dominate. This special magnetic field geometry has comparable poloidal and toroidal components at each point within the plasma. Field lines wrap around toroidal surfaces called flux surfaces, in this way field lines can be grouped by what flux surface the lie on, and the entire magnetic field constitutes a set of nested tori of flux surfaces.

The fields are maintained by associated toroidal and poloidal plasma currents. Its magnetic geometry is much like a spheromak, the distinction between them is primarily that a compact torus is being accelerated by a large railgun current, whereas a spheromak is formed at rest with respect to the laboratory. Also, spheromaks are formed in large, roughly spherical vessels, while the coaxial vessel allows the compact toroids to have almost any aspect ratio, and can range from doughnut shapes to long, cigar shapes.

A more detailed account of the theory of the magnetic equilibrium of compact toroids and spheromaks will be presented in Chapter 2. The CT has a long lifetime of over 1 ms and is able to hold itself together under some rather large forces. The compact toroids formed on CTIX are classified as low beta plasmas, where beta is the ratio of the hydrodynamic thermal pressure to the magnetic pressure. This is important because it means that magnetic effects will dominate pure hydrodynamic effects, and so certain approximations become convenient to use.

There is a large toroidal magnetic field behind the CT, initially generated by the railgun current flowing in the center conductor. This field becomes spatially uniform and steadily dies down as the column of magnetized plasma behind the CT expands, thereby driving the acceleration of the compact toroid.

As it leaves the accelerator, CT plasma is relatively dense $n = 10^{14}$ particles per cm^3 and of modest temperature $T_e = T_i = 50eV \sim 580,000$°K.

Measured surface magnetic fields at the edge of the CT are large $B \sim 1kGauss$ to $5kGauss$ and internal magnetic fields are expected to be a factor of 3 to 10 times larger.

The CT plasma is self confined, in a minimum energy equilibrium configuration. Low therma Beta, high kinematic beta.

Impurities in the plasma emit plenty of light $10^{17} photons/cm^3\ sec$ and is optically thin in the visible range.

Fluid Reynolds number $= V_{CT}L/v = 100$ to 10^4Magnetic Reynolds number $= V_{CT}L/D_M$ $= 10$ to 10^4

1.4 Timescales within the life of a CTIX plasma

The innovative aspect of the CTIX design is that it is capable of sustained operation with a maximum firing rate of 0.2 Hz, (1 shot every 5 seconds). We will often refer to the firing rate of CTIX as its rep rate or repetition rate. When we were taking data the rep rate was typically 0.05

Hz (1 shot every 20 seconds) so that the vacuum vessel could be fully pumped back down to base pressure between shots.

The standard firing rate is sufficiently fast to be able to take 1000 shots a day. If the pumping rate was significantly increased (or injected gas volume was decreased), in principle the repetition rate could be increased to 1 kHz if the capacitors could be maintained at high voltage.

CTIX's rapid fire ability is due to the fact that it is passively switched. The only active thing we do in firing CTIX is to trigger the gas valve to let a puff of gas into the formation section, which is already energized to a steady high voltage of typically 10 kV. Then at some randomly occurring time later, the gas ionizes due to the formation potential, thereby completing the formation circuit.

After a fixed delay of about 4 μs that allows the magnetized plasma to expand into the acceleration region and relax into a CT geometry, the accelerator circuit fires, which accelerates the CT to its injection velocity.

The whole system is passively dependent on the event of the gas break-down which means that CTIX can fire any number of times in quick succession at what ever rate you can successfully send in distinct pulses of gas. The only limitation is that presently the capacitors loose their charge after only one firing cycle.

The basic operations of CT formation and acceleration have been demonstrated to operate very robustly, with a nearly failure-free production of compact toroids over the course of more than 60,000 firings of CTIX. Although CTIX almost never fails to produce and accelerate viable CT's, there is a noticeable amount of random variation of CT properties from one shot to another. With all experimentally controllable settings of the device held fixed, important observables such as plasma density, CT magnetic field shape and strength, and CT final velocity, will jump around randomly within some finite range. These fluctuations are attributed to uncontrollable variations in the initial conditions during the CT formation process.

For example, the formation gas valve sometimes lets in a little more hydrogen then average, sometimes less, resulting in a correspondingly greater or lesser CT plasma density. Another

uncontrollable event is the ionization of the neutral hydrogen (called the breakdown), which will occur at a randomly occurring time, that can vary as much a several milliseconds.

The time of breakdown should depend on the density of the formation cloud of neutral hydrogen, the strength and geometry of the formation magnetic field that acts to bend the trajectories free charged particles, and it most critically depends on the some spontaneous creation of enough free electrons (possibly via cosmic rays) to trigger the needed runaway cascade of electron impact ionization. Overall, there are many more questions than answers regarding the details of the formation process.

Along CTIX there are a number of magnetic field probes. Each is capable of resolving poloidal and toroidal components of the magnetic field at the outer edges of the CT. These different components are recorded on separate digitizer channels. We have three magnetic probes situated along the length of the accelerator at 57 cm, 91 cm, and 142 cm from the gas valve. The B_z probe signals are used on a daily basis for to see the existence of the CT and to get a quick estimate of its velocity.

1.5 Typical CTIX Plasma Parameters

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Densities of $n_e = n_i = 10^{14}$ to $10^{15} cm^{-3}$, hence a plasma frequency of $\omega_p \sim 20 GHz$ Peak magnetic field inside CT: $B_\theta = B_z = 1$ to 10 kGauss Electron Temperature Varies from 10 eV to 80 eV Debye Length $\lambda_D = 7\times10^{-5}$ to $7\times10^{-4} cm$ Electron Gyroradius inside CT = $7\times10^{-4} cm to 0.02 cm$ The DDT toroidal field coils have a radius of 40 cm and produce about 3 Gauss per Amp at the center of the minor axis of the vacuum vessel. They are water-cooled and have achieved a maximum field of 600 Gauss in continuous mode.

[should I include a section listing diagnostics?]

A number of current monitors were in use for diagnosing what is going on within the CTIX

accelerator circuit. These measured currents flowing between different parts of the machine as a function of time. They were also useful to track down sources of ambient noise and minimize the effect of such sources.